

**TOWARD AN IMPROVED UNDERSTANDING OF  
THE GLOBAL FRESH WATER BUDGET**

Symposium on Living with a Limited Water Supply  
85<sup>th</sup> AMS Annual Meeting, 9-13 January 2005, San Diego

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**1. INTRODUCTION**

The major components of the global fresh water cycle include the evaporation from the land and ocean surfaces, precipitation onto the ocean and land surfaces, the net atmospheric transport of water from oceanic areas over land, and the return flow of water from the land back into the ocean. The additional components of oceanic water transport are few, principally, the mixing of fresh water through the oceanic boundary layer, transport by ocean currents, and sea ice processes. On land the situation is considerably more complex, and includes the deposition of rain and snow on land; water flow in runoff; infiltration of water into the soil and groundwater; storage of water in soil, lakes and streams, and groundwater; polar and glacial ice; and use of water in vegetation and human activities.

Knowledge of the key terms in the fresh water flux budget is poor. Some components of the budget, e.g. precipitation, runoff, storage, are measured with variable accuracy across the globe. We are just now obtaining precise measurements of the major components of global fresh water storage in global ice and ground water. The easily accessible fresh water sources in rivers, lakes and snow runoff are only adequately measured in the more affluent portions of the world. Present proposals are suggesting methods of making global measurements of these quantities from space. At the same time, knowledge of the global fresh water resources under the effects of climate change is of increasing importance as the human population grows.

This paper provides an overview of the state of knowledge of the global fresh water budget, evaluating the accuracy of various global water budget measuring and modeling techniques.

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We review the measurement capabilities of satellite instruments as compared with field validation studies and modeling approaches.

Based on these analyses, and on the goal of improved knowledge of the global fresh water budget under the effects of climate change, we suggest priorities for future improvements in global fresh water budget monitoring. The priorities are based on the potential of new approaches to provide improved measurement and modeling systems, and on the need to measure and understand the potential for a speed-up of the global water cycle under the effects of climate change.

**2. THE GLOBAL WATER CYCLE**

The principle storage and flux components of the global water cycle—precipitation, evaporation, atmospheric transport, runoff, storage in the ocean and on land—have been the subject of extensive research over many years (WCRP, 1990; Chahine, 1992; Gleick, 1993). We will first review the accuracy of present and planned satellite measurement capabilities for measurement of major components of the global water cycle; precipitation, evaporation, atmospheric transport and continental runoff. A following discussion will review additional components, which are primarily fresh water storage components and include polar and glacial ice, ground water, soil moisture, etc.

**2.1. Precipitation**

Global precipitation has small temporal and spatial scales, typically on the order of less than an hour and a few km. Precipitation also has strong latitudinal and spatial/seasonal variability. Due to the variability in types of weather systems, the tropical, mid latitude and polar regimes have significantly differing weather systems and hence, problems with respect to measurement. For these and other reasons, the errors in precipitation measurements and model outputs are significantly different in the different climate zones around the world and may vary from season to season (e.g.,

see Chahine, 1992). The two major global precipitation data sets (Xie and Arkin, 1992 and GPCP-Huffman et al, 1997) are based on combinations of satellite, raingage, model calculations and other data. These and two other datasets have significant differences of up to twenty percent in the latitudinal bands having peak precipitation, such as the ITCZ and the upper latitude storm tracks (Large and Yeager, 2003). The GPCP data provides ~20% more rainfall in the tropics, and lower values in the mid latitude storm tracks. Similar variability can be found when comparing these observational datasets with global analyses from the NCAR/NCEP or ECMWF re-analyses. Additional errors arise. Over land global precipitation measurements are of reduced quality, except where they are supplemented by ground based radars and raingages, this is because the land surface is more emissive than ocean and therefore masks precipitation returns except for high frequency passive radiation. Also, frozen precipitation, particularly at high latitude cannot be measured with current passive satellite systems.

## **2.2. Evaporation**

Direct measurement of Earth evaporation fluxes is difficult, usually only provided in dedicated field campaigns or small flux networks. For widespread use in numerical models, the surface fluxes are calculated using bulk formulas which, due to the non-linearities in flux physics (e.g. Taylor, 2000; Large and Yeager, 2004 and others), have well known limitations. These bulk formulae also provide the basis for surface flux estimates from satellites. Comparisons of satellite and surface validating measurements from ocean field experiments (Chou et al., 2004) are suggestive of rms scatter between the satellite and field validation measurements of about 20%, and correlation of ~0.8 between the satellite and validation. There were also some systematic differences that vary with the intensity of the flux, with satellite underestimates at low values, transitioning to overestimates at high values. The key source variables, surface air speed and humidity, and air-sea humidity difference have some intensity-related variability over the range of conditions observed in the field experiments. Chou et al also report similar differences between the satellite data and analysis fields including HOAPS, NCEP, and the de Silva fields. These comparisons indicate that although the global and latitude band differences are small, there are significant latitudinal and regional differences of up to ~20%

wind speed, ~10-15% surface humidity, and resulting ~20-30% latent heat flux differences between the satellite and analysis fields. The net effect is that the correlation between the satellite and the best analysis fields range from ~0.8 for HOAPS and NCEP, to ~0.5-0.7 for de Silva. Due to the extremely variable topography and vegetation, land surface heat flux estimates are highly variable, as compared to the oceanic surface latent flux values; Lohmann, et al (2004) report mean annual evapotranspiration differences of about a factor of two between different land surface models.

## **2.3. Water Vapor Transport**

Knowledge of global water vapor profiles is hindered by dependence on land-launched radiosondes, and by the lack of adequate calibration standards. Satellite global water vapor profiles have been produced from TOVS Path A (Susskind et al., 1997) and HIRS2/MSU, and higher quality water vapor profiles are now being derived from AIRS/AMSU-A with an expected integrated precipitable water (IPW) accuracy of 15% in 1 km layers (Susskind et al., 2003). Evaluations of AIRS accuracies as compared with radiosondes and GPS techniques (McMillan, et. al, 2005) suggest that the AIRS IPW compares at ~11%, well within the 15% design goal, with the other measurement systems, provided that AIRS sampling requirements (e.g. cloud clearing) are met. The comparison between the radiosondes and GPS in Miller et al (2004) is slightly better than with AIRS (~7% rms difference v. 11%), with also less bias between the instruments. This suggests the possibility that AIRS algorithm refinement may reduce these uncertainties. The net effect of these excellent AIRS results is that the major measurement issues relating to water vapor transport relate to the ability to correctly transport water vapor from oceanic to continental areas. The major needed addition to these measurements is, of course, significantly improved global wind fields (e.g. see the call by Emanuel et al, 1998). New concepts for wind measurements include space Doppler lidar systems, and approaches as suggested by Riishojgaard (2005) that are based on feature tracking approaches similar to that used for water vapor winds.

## **2.4. Continental Discharge**

Continental discharge of water back into the oceans balances the global fluxes of water vapor, plus changes in storage and other imbalances.

Extensive studies over the past three decades have reduced the discrepancies between analyses of runoff to a few percent (Dai and Trenberth, 2002; Fekete and Vorosmarty, 2002); however, since there are few measurements, significant assumptions are required over vast portions of the globe. The storage and fluxes in streams and rivers are poorly observed, with measurement of only major rivers, except in the affluent world. A significant portion of the global water drainage occurs in large drainage basins with large wetlands and in large remote watersheds. Roads et al. (2003), evaluating the relatively well instrumented Mississippi basin, found model predictions of runoff can be in error by 50% or more; Roads et al. (2003), and Coe (2000) found similar results, and Large and Yeager (2004) needed similar adjustments for their ocean GCM, and cite the estimate that only about 50% of runoff, worldwide is measured through river gage measurements. Lohmann et al. (2004) report regional differences of up to about a factor of four in mean annual runoff between differing land surface models.

## **2.5. Storage of water in global ice**

The storage of water in glaciers and polar ice—a fundamental portion of the global water cycle—fluctuates in response to climate change (Laxon et al., 2002; Comiso, 2002, 2003), and is a significant contributor to sea level fluctuation. Past mapping of Greenland using airborne altimetry—and more recently using space radar altimetry, plus visible imaging with MODIS—clearly shows melting and the acceleration of glacier drainage around the Greenland margin. The recent launch of ICESat, which provides ice sheet altimetry with better than 10 cm accuracy as measured over 70 m spot sizes, (Zwally et al., 2002), has demonstrated the potential for greatly enhanced measurement accuracy of water storage in glacial and polar ice, and promises to significantly alter the approaches and knowledge of water storage in ice.

## **2.6. Soil moisture**

The large spatial variability in soil, together with variability of underlying strata, strongly affects the water holding capacities: soil moisture would ideally be measured on km scales. Similarly, due to the time scales of precipitating weather systems and high evapotranspiration rates, soil moisture varies on diurnal to daily time scales. The surface partitioning of precipitation into runoff and infiltration is determined by soil variability and

antecedent soil moisture. Soil moisture is therefore poorly monitored, and measured, both locally and globally. Shallow surface measurements are just now available from AMSR-E (Njoku et al., 2003). Intercomparison of North American soil moisture fields in the Land Data Assimilation System (LDAS – Schaake et al., 2004) found the storage of water in this relatively well instrumented continent to be “highly model dependent”. The planned HYDROS and SMOS missions will provide measurements at 10–40 km scales, greatly improving knowledge of land surface soil moisture.

## **2.7. Ground Water**

Ninety-six percent of Earth’s unfrozen fresh water exists as ground water (Shiklomanov, 1993). Although ground water storage varies slowly compared with other terrestrial water stocks, it is an important indicator of climate and water cycle variability (Alley et al., 2002). The Gravity Recovery and Climate Experiment (GRACE) satellite mission provides the first space estimates of terrestrial ground water storage (Rodell et al., 2002, 2005). Although the spatial resolution of GRACE-derived water storage information is low, these measurements constrain land surface models, and are providing a better understanding of the characteristics and importance of groundwater as a water cycle variable.

## **2.8. Seasonal snow**

Terrestrial snow is an important component of the water cycle, providing significant fresh water for human use, affecting the energy and water dynamics of terrestrial hydrological systems and the lower atmosphere. Snow cover extent is provided by MODIS (Hall et al., 2002) and by passive microwave measurements from SSM/I and AMSR-E (Chang et al., 2003). However, the actual snow water content (SWE), or snow mass measurements, are less mature and presently require regional to global validation. The AMSR-E instrument aboard the Aqua satellite currently provides global SWE estimates (Chang et al., 2003), and field experiment campaigns (e.g. Cold Lands -- CLPX) offer validation opportunities. However, North American Land Data Assimilation System (NLDAS) comparisons of model simulations of SWE, with validating measurements from SNOTEL (Pan et al., 2003) indicate significant—more than a factor of two—underestimates between the modeled and measured SWE. Pan et al. were able to show significant improvements in the data assimilations

through use of local corrections to the precipitation assumed in the NLDAS calculations. This provides hope for considerable improvements in future SWE measurements from space.

## **2.9. Land Data Assimilation Modeling**

An important component of understanding the complex continental water cycle budget resides in computer models that ingest land water cycle measurements to produce water analyses and forecasts. Newly developed large-scale Land Data Assimilation Systems (LDAS), and the 1/8 degree North American LDAS (Mitchell et al., 2004), the 1/4 degree Global LDAS (Rodell et al., 2004) and the 1km Land Information System (LIS; Peters-Lidard et al., 2004) are among a growing spectrum of LDAS models that are providing new approaches to the diverse water cycle data sources—satellite-based precipitation, radiation, and surface parameters, in addition to model-derived surface meteorology—in a computer forecast venue. Designed to support fresh water budget studies as well as applied uses, these LDAS systems can evaluate the contribution of each component of the water cycle to the full water cycle, and when fully developed will assist in understanding the importance of improved measurement of individual components to error reduction of the whole.

## **3. DISCUSSION – A PATH TO THE FUTURE**

The review above suggests that while many components of the global fresh water cycle are measured, there remain many gaps, as well as large measurement uncertainties, that together prevent an accurate budget from being formulated. The following paragraphs examine goals for the future.

### **3.1. Precipitation**

The major goals for accurate long term monitoring of precipitation center on completion of the planned Global Precipitation Mission as an international effort that is complete with transition to operational status. The excellent success of TRMM, and the extensions to the use of MASR-E data, indicates this need, and gives hope that the ~ 20% uncertainties global precipitation seen in the comparisons of global precipitation measurements will be reduced with an improved core GPM satellite having a multi-wavelength radar that can see less dense precipitation, plus other future upgrades that could add higher

frequency passive microwave measurements. These changes would significantly improve the global precipitation measurement accuracy.

### **3.2. Evaporation**

The present results are better than some anticipated, providing ~20% uncertainties in the oceanic latent heat flux, or surface evaporation rate. Future potential upgrades can come from improved algorithms and possibly from future sea surface salinity measurements, which when coupled with rainfall could provide another approach for estimation of evaporation. However, all things considered, this is a tough problem to solve, given current approaches; other goals seem more tractable.

### **3.3. Water vapor transport**

Present capabilities for satellite measurement of water vapor profiles have been significantly improved with the development of AIRS. The major area for improvement of water vapor transport will be in the area of improved global tropospheric wind measurements, such as suggested by Riishjogaard (2005), or possibly with other technologies. Tropospheric winds are of extremely high priority for many other reasons.

### **3.4. Continental discharge**

The current calculations of continental discharge using direct measurements, and requirements of ocean GCMs all point to a very serious gap in knowledge concerning continental discharge. For these reasons, the proposed surface water satellite mission (Alsdorf and Lettermaier, 2002; Alsdorf et al., 2003) is a very high priority. They propose the use of high resolution satellite altimeters for monitoring global surface water levels and stream flow rates. The great promise shown by ICESat measurements clearly demonstrates the feasibility of the altimetry; problems remain in converting river stage into stream flow, particularly in large braided flood plains. Nevertheless, the potential for significant improvement here is very high.

### **3.5. Global Ice**

ICESat has been wonderfully successful at demonstrating the ability to measure ice sheet altimetry to far better than the designed 10 cm. It has new application to sea ice, continental discharge (as noted above), and vegetation

structure. With the remaining technological issues solved, this technology is ready for transition to an operational climate observational status.

### **3.6. Soil Moisture**

Although soil moisture remains largely un-measured globally, the upcoming NASA/HYDROS and European/SMOS satellites will quickly change knowledge of global soil moisture, once they are launched. These measurements will assist in improved short term climate and precipitation forecasting as well as abilities for linking climate and precipitation with vegetation stress indexes.

### **3.7. Ground Water**

The current GRACE mission is significantly improving our ability to resolve and understand variability in the earth's gravity field and ground water. New technologies should significantly improve these capabilities in the future.

### **3.8. Seasonal Snow**

In order to make significant advances in knowledge of the storage of water in seasonal snow, significantly improved, high resolution satellite measurements are needed. To a first order, these measurements could come from high resolution altimeter systems, such as already discussed for global ice, and continental discharge. The prospects for other approaches, including active or passive microwave systems remain as very interesting developments.

### **3.9. Land Data Assimilation Modeling**

The capabilities of the land data assimilation models (e.g. Mitchell et al, 2004) are a key to optimally using the measurements in numerical analysis and forecast models. It remains extremely important that these efforts continue. Critical elements of this effort include the close linkage of the LDAS efforts with both the observational community and the numerical weather prediction community, plus continued provision of the high-end highly parallel processing support needed for the high resolution numerical LDAS models.

## **4. DISCUSSION**

Based on the discussion above, we can define the priorities for new instrumentation improvement in the observation of the global fresh water cycle.

The following priorities assume the present goals for research satellites and the transition through NPP to NPOESS:

- precipitation measurement along the lines of GPM, but enhanced to improve measurement of high latitude and ice precipitation,
- global tropospheric wind measurement with high enough spatial/temporal/vertical resolution that synoptic/sub-synoptic weather forecasts are significantly improved,
- high precision (2-3 cm) global satellite altimetry measurements that meet the needs of polar ice sheets, glaciers, snow pack depth, and river flow/continental discharge.
- the currently planned new research satellite systems for measuring soil moisture and sea surface salinity (HYDROS, Aquarius, and SMOS) are extremely important additions.
- Continued support of LDAS activities including the operational community relationship

Each of these concepts has a strong scientific and technological basis, upon which we can expect success, including a smooth transition to operational status with future upgrades. For each of these systems, the requirements of scientific oversight and production of "climate data records" is mandatory. This dictates a continued close relationship between the operational community that will use these instruments in the future, and the scientific community that will provide the needed ongoing improvements in calibration and for future upgrades in measurement capabilities.

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